Responses to Elevated CO2 on Food Production and Life Support Systems in a Mars Habitat

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Plants are highly complex systems that demand precise environmental management for optimum growth and production and express species-specific responses to the over-supply or deprivation of particular growth-driven resources. Elevated atmospheric carbon dioxide (eCO_2) has been linked to plant responses including the amount of atmospheric carbon dioxide (CO_2) sequestered, nitrogen (N_2) absorbed from the soil, water vapor produced, amount and nutrient composition of edible biomass yield, and more. In closed-loop ecosystems such as a Mars habitat, the cascading and compounding impacts of these responses on the interrelated biological and mechanical systems can be significant. This study leveraged decades of experimental data and modeling of plant responses to eCO_2 (motivated primarily by climate change research) to explore its impact on food production and life support systems in a Mars habitat. A species-specific model of responses to ambient CO_2 on plant CO_2 consumption, transpiration and biomass production was integrated into SIMOC, an agent-based model (ABM) used for high-fidelity Environmental Control and Life Support System (ECLSS) and bioregenerative life support (BLSS) simulations. Several scenarios were defined with varying combinations of humans, ECLSS components, and different amounts and of crop species. A target CO_2 level was defined for each simulation and the relevant ECLSS components programmed to add or remove CO_2 as necessary to maintain this level. For each scenario, simulations were conducted with the ABM at different target CO_2 levels and all components of the system were monitored. Maintaining elevated levels of CO_2 was shown to increase crop yields and reduce crop water demand, and reduce the load on ECLSS and power production systems in some cases.

Nomenclature

$ECLSS$ = environmental control and life support system(s)
$BLSS$ = bioregenerative life support system(s)
eCO_2 = elevated CO_2 (i.e., >350 ppm)
$FACE$ = free air CO_2 enrichment
ABM = agent-based model
RUE = resource use efficiency
TE = transpiration efficiency
SLA = specific leaf area
CNC = critical nitrogen concentration
ppm = parts per million
Q = accumulated biomass
I = intercepted radiation
f_s = stress factor
f_c = carbon dioxide factor
C_i = carbon dioxide compensation point
T = temperature
W_d = water demand
$f_{c,TE}$ = carbon dioxide factor for transpiration efficiency

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I. Introduction

THE vision of humanity living among the stars increases in focus and resolution every day. Projects like Sierra Space and Blue Origin's Orbital Reef, NASA's Artemis Program, and SpaceX's Starship propose off-world communities at greater distance, scale and duration than have yet been implemented.

Environmental control and life support systems (ECLSS) support human habitation by maintaining a breathable atmosphere, recycling water, processing waste and regulating temperature. The ECLSS aboard the ISS and current spacecraft are mechanical.[1] Bioregenerative life support systems (BLSS), or artificial ecosystems which purify water, revitalize the atmosphere and generate human food simultaneously,[2-3] are a promising alternative or compliment to ECLSS. Live experiments into BLSS have been underway for decades, both private (Biosphere 2, MDRS) and public (NASA's CELSS and ESA's MELiSSA).[3-6] These experiments typically include hybrid life support systems with mechanical and biological components, sometimes include humans, and test the regenerative capacity of various growing methods and plant species - from traditional food cultivars like wheat and lettuce, to specialized organisms like mealworms, bacteria, and algae.

Elevated carbon dioxide concentration (eCO_2) response is one of many selection criteria for plant species in BLSS.[2] At first glance, operating at eCO_2 would appear to greatly benefit BLSS by increasing the rate of CO_2 sequestration and biomass accumulation. Coincidentally, research into plant response to eCO_2 has been underway for decades in order to understand and forecast the effects of climate change. Hundreds of live experiments - most notably Free-Air CO_2 Enrichment (FACE) studies, which attempt to mimic realistic field conditions - generally find that eCO_2 results in an increase in photosynthesis and growth and reduced stomatal conductance and transpiration.[7-8]

Agent-based models (ABMs) are simulations the interactions of autonomous entities in a closed system over time which provide insight into the emergent behavior of the system; they are frequently used to test designs and parameters for both BLSS and plant response to eCO_2.[9-10]

Our study combines current models of BLSS and plant response to eCO_2 into a single ABM. An obvious limitation of ABMs is that insights are constrained by the fidelity of the constituent agents. As such, we do not aim to prescribe specific design parameters for BLSS under eCO_2; we instead use available data and models to explore the direction and relative magnitude of responses to eCO_2, and the combined effect of those responses on the habitat as a whole.

II. SIMOC Description

SIMOC (a Scalable, Interactive Model of an Off-world Community) includes an ABM designed to simulate a small Mars habitat. It includes built-in models for several agents including humans, 22 unique plant species, 10 mechanical ECLSS components, habitats and greenhouses of various sizes, and solar power generation, as well as several currencies of exchange, such as potable water and kilowatt-hours (kWh). Agent models define 'input' and 'output' currency exchanges, each of which specifies a rate per unit time and a link to the agent to/from which the currency is exchanged. Exchanges can also include optional parameters such as a deprivation period after which the agent dies, a daily or lifetime growth function, or a threshold which activates the agent based on environmental conditions. Simulations are configured by specifying amounts of agents and their associated response parameters. The simulation then proceeds by discrete time steps (1 hour by default); at each time step, agents are called one-by-one to execute their responses and currency exchanges. Agent specifications are taken from NASA's Life Support Baseline Values and Assumptions Document (BVAD), direct communication with NASA researchers and published literature.

The SIMOC plant model includes input currency exchanges for carbon dioxide (CO_2), potable water, fertilizer and kWh (to represent artificial lighting), and outputs for oxygen (O_2), water vapor and internally accumulated biomass. (The current version of SIMOC employs potable water for both humans and plants, while in reality water used for plants requires less process and fewer additives than that for human consumption; future version will differentiate potable and clean water.) Each plant model specifies average hourly values for each exchange, as well as a 'lifetime' parameter. At the start of each simulation, currency exchange values are mapped over the plant's lifetime using the specified growth function so that the lifetime average value remains the same, but daily/hourly values reflect the expected life cycle of the plant. Biomass accumulation assumes fixed plant spacing and uses a normal curve (i.e., plants grow quickly in the middle of their life cycle and more slowly at the beginning and end), and all other exchanges use a sigmoid curve (i.e., mature plants' metabolic processes consume and produce more resources). In addition, all exchanges are distributed across the day/night cycle. Hourly values for the plant's entire lifetime, illustrated in Figure 1, are pre-calculated at the beginning of a simulation; if there is a shortage of CO_2, fertilizer, light or potable water, growth is paused, and if it persists past the deprivation period (e.g., 72 hours for

CO_2), the agent dies. At the end of the life cycle, the internally accumulated biomass is harvested and converted to edible food and inedible biomass at a specified ratio, and the plant is either resown or removed from the simulation.

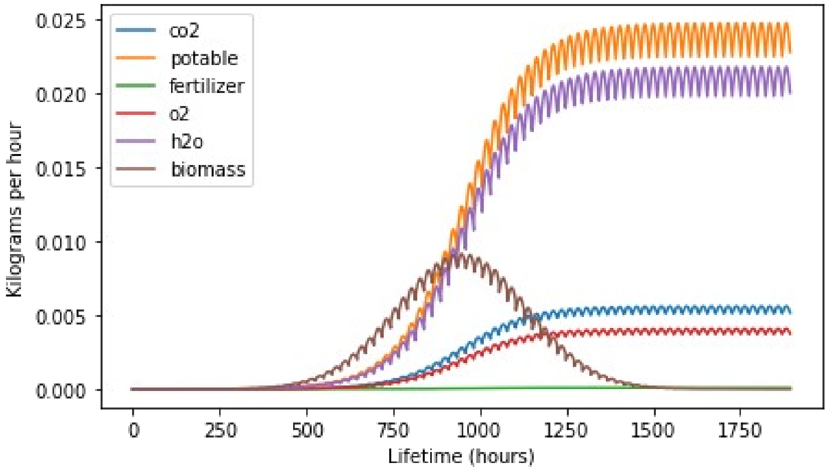

Figure 1. SIMOC Wheat Expected Step Values. *Excluding kWh (light) and harvest currencies. Fertilizer values follow similar daily/lifetime growth curves, but values are too small to be visible in this chart.*

III. Plant Response to eCO_2

A. Modeling Plant Response to eCO_2

Experiments on plant responses to eCO_2 date back to the 1970s and included greenhouse, growth chamber, open-top and field experiments. Beginning in the 1980s, large amounts of data were generated by Free Air CO_2 Enrichment (FACE) studies for various crop species and under varying environmental conditions. One meta-analysis of 437 FACE studies found an average relative increase in yield of 1.36 for mature agricultural crops under eCO_2.[7] Mathematical models have been developed from these data at varying levels of complexity, incorporating different environmental inputs such as temperature, solar radiation and soil moisture. The increase in yield from eCO_2 is typically attributed to two primary mechanisms: an increase in photosynthetic efficiency, or the rate of photosynthesis under ideal lighting; and a decrease in stomatal conductance, the rate of internal nutrient and water transport.[11]

Our approach to modeling these mechanisms is based on Ref 12, which is also the basis of the APSIM-Wheat model (discussed in detail below). They identify four variables, which are affected by CO_2 concentration:

- Radiation use efficiency: (RUE): the rate at which the plant creates new biomass from light, water, CO_2 and nutrients, provided all are available. Elevated CO_2 or increased temperature can increase RUE.
- Transpiration efficiency (TE): the rate at which water is taken up through the roots and lost via transpiration during photosynthesis. This is referred to elsewhere as Water Use Efficiency and is typically measured terms of biomass per unit of water, or on a gas exchange basis as water transpired per unit of CO_2 fixed.[15] eCO_2 increases TE, resulting in less water being used for the same rate of photosynthesis.
- Specific leaf area (SLA): The portion of accumulated biomass allocated to leaves. eCO_2 increases the proportion of non-structural carbohydrates, thereby decreasing leaf area.
- Critical nitrogen concentration (CNC): the minimum nitrogen concentration required for optimal growth. eCO_2 reduces CNC.

B. Sample Implementation: APSIM-Wheat

APSIM (Agricultural Production Systems sIMulator) is an open-source ABM used to model crop production under various environmental conditions. It includes sub-modules for several plant species and soil profiles based on published literature, and incorporates historical environmental data from different regions.

APSIM simulates the food output of different crops over time in response to varying environmental conditions. As detailed in Ref 13, daily growth is centered around daily biomass accumulation, which is determined by current leaf area, stage of growth, temperature and light, and can be limited by stress factors related to soil water or nitrogen, or increased by a CO_2 concentration above 350 parts per million (ppm).

APSIM-Wheat, a sub-module of APSIM, defines the increase in accumulated biomass (ΔQ) as the product of intercepted radiation (I), radiation use efficiency (RUE), stress factor (f_s) and a carbon dioxide factor (f_c), as shown in Equation 1.

$$\Delta Q = I \times RUE \times f_s \times f_c \tag{1}$$

The effect of eCO_2 on RUE is accounted for by the carbon dioxide factor (Equation 2), which is calculated using the baseline CO_2 concentration of 350 ppm (350), current CO_2 concentration (ppm), and the CO_2 compensation point (C_i, Equation 3). The CO_2 compensation point accounts for the impact of temperature on RUE, and is calculated using daily mean temperature (T).[16]

$$f_c = \frac{(ppm - C_i)(350 + 2C_i)}{(ppm + 2C_i)(350 - C_i)} \tag{2}$$

$$C_i = \frac{163 - T}{5 - 0.1T} \tag{3}$$

TE is accounted for by water demand (W_d, Equation 4), which in turn determines the soil water uptake rate and the rate of transpiration. TE (Equation 5) is defined by a growth-stage dependent TE coefficient (f_{TE}) and a temperature-dependent vapor pressure deficit (VPD), scaled by the CO_2 factor for transpiration efficiency ($f_{c,TE}$), linearly interpolated between 1 and 1.37 at 350 and 700ppm respectively. Other factors, especially relative humidity and temperature, affect TE via the VPD calculation, but are not considered in this study as our focus is on CO_2.

$$W_d = \frac{\Delta Q}{TE} \tag{4}$$

$$TE = f_{c,TE} \frac{f_{TE}}{VPD} \tag{5}$$

SLA affects the leaf area index, and is part of the calculation of intercepted radiation. CNC is incorporated into the stress factor, which is the lesser of the optimal temperature and nitrogen factors. These two fields are not incorporated into SIMOC, as leaf area and nitrogen are not part of the current SIMOC plant growth model.

IV. Modification of SIMOC Model

A. Applying Plant Response to eCO_2

These responses to eCO_2 are incorporated into SIMOC as scalar multipliers on the currency exchanges related to the respective processes, shown in Table 1.

- f_c accounts for the change in photosynthetic efficiency. In APSIM-Wheat, it increases accumulated biomass linearly, and subsequently all input values that are proportional to the plant's biomass: water, CO_2, oxygen and nutrients.
- $f_{c,TE}$ accounts for the change in stomatal conductance. In APSIM-Wheat, it decreases the water demand linearly, which affects water taken in through the roots and water evaporated from the leaves.

Table 1. SIMOC wheat currency exchanges under eCO_2.

Currency (kg/hr)	350ppm	eCO_2 scale	700ppm
In			
CO_2	.00254	$\times f_c$	.00316
Potable water	.01125	$\times 1 / f_{c,TE}$	.00821
Fertilizer	.0000388	$\times f_c$	.0000482
kWh (light)	.801	-	.801
Out			
O_2	.001852	$\times f_c$	.00230
Water vapor	.00989	$\times 1 / f_{c,TE}$	.00722
Biomass	.00208	$\times f_c$	.00259
Harvest			
Food	biomass × 0.4	-	biomass × 0.4
Inedible Biomass	biomass × 0.6	-	biomass × 0.6

Because currency exchanges in and out are not mapped 1-to-1 in SIMOC, these calculations have a slightly unequal effect on input and output currency exchanges. Thus an additional step is added to scale outputs proportionally to match inputs based on mass.

B. Dealing with Volume-Related Perturbations

When plants comprise a significant proportion of the pressurized volume of an enclosed habitat, their gas exchanges (CO_2, O_2 and H_2O) are significant relative to the overall total internal atmosphere. The magnitude of these exchanges is affected by the size/maturity of the plant, as well as the rate of photosynthesis - which only occurs when light is available to the leaves. The net result is that constant compensation by mechanical ECLSS is needed, and the rate of compensation varies over the day/night cycle and over the plant's lifetime.

Atmospheric CO_2 concentration must be maintained at or near the target level in order to accurately assess the effects of eCO_2. SIMOC uses an hourly time step by default, and in scenarios where the proportion of plants relative to pressurized volume is high, plants consume more CO_2 in 1 hour than is contained in the entire atmosphere. Additional modifications to the SIMOC model were made to mitigate these effects:

- Plants in SIMOC typically rely on the CO_2 produced by humans. When this is insufficient, either due to the size of the plants or lifecycle effects, supplemental CO_2 is required. We add a CO_2 storage tank, which contains a starting quantity and is added to by CO_2 removal agents. A CO_2 makeup valve releases CO_2 back into the controlled environment when concentration falls below the target threshold. In the scenarios below, this threshold is set to the target PPM, and the CO_2 removal agents are set to the target PPM plus some buffer, e.g., 100 ('ppm buffer').
- Each plant agent's growth is based on the current CO_2 concentration. Because plants are called one-by-one and each plant also affects the CO_2 concentration, plants that are called later effectively respond to a different atmosphere. To account for this, the CO_2 response variables are cached by the first plant called in a time step.
- In certain situations, the plants (together) require more CO_2 in 1 hour than is contained by the atmosphere. In reality, CO2 would be added continuously as needed from the CO_2 storage tank. To mimic under SIMOC's hourly time step, A 'priority' system was implemented where, if the atmosphere was depleted by plants called earlier in the time step, they draw from CO_2 storage directly.
- ECLSS agents in SIMOC were designed to operate at a pre-defined rate, and switch on or off depending on environmental conditions. When this system is scaled up, it creates large fluctuations in CO_2 concentration. We implement a simple rate-find algorithm: ECLSS agents calculate the total delta in their target currency from the previous time step, use this to forecast the concentration for the current time step, and set their rate to result adjust this forecast to meet the target.

V. Simulation Scenarios

Two eCO_2 configurations are used: one with a garden sized to offset human CO_2 production ('offset'), and one to produce enough food (at maturity) to support the humans ('full'). Two scenarios are used for each configuration: one with a target CO_2 concentration 350ppm, and one at 700ppm. Additionally, a scenario with no garden ('base') at 350ppm is used as a reference. All scenarios also include sufficient power generation, potable water, fertilizer, CO_2 reserves and food rations to cover demand. Crew Habitat and greenhouse are initialized with earth-normal atmospheric pressure and composition. A constant temperature of 25°C is assumed. Table 2 shows the initial parametrization of all scenarios.

The human model in SIMOC specifies CO_2 production of 1.08 kg/day,[14] which is offset by a garden size of 27.9 m^2/person, or 84 m^2 total of mature plants. Common practice is to grow seedlings in a dense arrangement for the first 12-14 days and then increase spacing, but this feature is not currently included in SIMOC, so the mature area requirements are used for the full lifetime.

The NASA BVAD specifies a baseline metabolic requirement of 12.99 MJ (3,104 kcal) per crew-member per day (Section 4.51), which gives a garden size of 100.6 m^2 per person, or 302 m^2 total. This value, calculated for a 95th percentile (84 kg) crew-member, is at the high end of the likely range; other studies, such as the Chinese Lunar Palace, have crew members weighing less than 45 kg who use consume less food and O_2. Nevertheless, this study uses NASA's baseline values.

Table 2. Scenarios Detail.

Scenario	Base	Offset	Full
Humans	3	3	3
Habitat Volume (m^3)	2,260	2,260	2,260
Garden Size (m^2)	0	84	302
Greenhouse Volume (m^3)	-	2,454	5,610
Target CO_2 concentration(s) (ppm)	350	350, 700	350, 700
PPM Buffer (ppm)	100	100	200
Max CO_2 removal rate (kg/hr)	0.17	0.17	0.425
Max CO_2 supplement rate (kg/hr)	-	0.17	1.7

The garden is configured as shown in Table 3 to provide a reasonably palatable menu for the human inhabitants, include a range of plant species in terms of resource intensity and caloric output, and give a suitable macronutrient distribution. Since eCO_2 response is modeled the same for all plant species, only one garden configuration is considered, and areas are scaled proportionally based on a specified total area.

Table 3. Garden Detail.

	Wheat	Peanut	Tomato	Radish	Total
Planted Area (m2)	.27	.33	.20	.20	1
CO_2 (kg/day)	0.0165	0.0147	0.0040	0.0036	0.0387
Calories (kcal/day)	18.68	11.57	0.40	0.20	30.85
Protein	14%	29%	24%	27%	18%
Carbohydrate	84%	13%	71%	68%	65%
Fat	2%	58%	5%	5%	17%

The NASA BVAD specifies an optimal macronutrient distribution of 50-55% carbohydrate, 30-35% fat, and 12-15% protein (Table 4.65). Of the plant species included in SIMOC, only peanuts, soybeans and chard have > 10% fat content, only peanuts have > 30%, and all three have > 15% protein content; thus our macronutrient distribution is non-optimal.

In all scenarios, plants are sown at the beginning of the simulation, harvested at the end of their lifetime, and re-sown. Resource consumption increases as plants mature, and the lifetimes of the selected crop species varies, so combined resource consumption is highly irregular early in the simulation when life cycles are aligned, and ‘flatter’ as time goes on and life cycles become staggered. The combined effect of CO_2 consumption is illustrated in Figure 2.

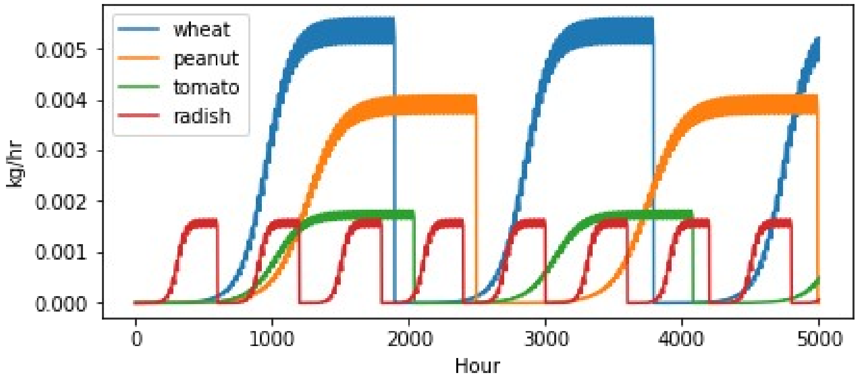

Figure 2. Expected CO_2 Consumption.

VI. Simulation Results

In both garden configurations, currency exchanges responded roughly as expected to eCO_2. In the ‘offset’ and ‘full’ scenarios, biomass production increased by 17.4% and 20.9% respectively, and CO_2 consumption increased by 18.8% and 23.2%, respectively. Table 4 shows the values of relevant currency exchanges at standard and elevated CO_2 in both scenarios.

Table 4. Total Plant Currency Exchanges. Average kg/hr

	Offset			Full		
	350ppm	700ppm	Delta	350ppm	700ppm	Delta
CO_2	0.1345	0.1598	+18.8%	0.4758	0.5862	+23.2%
Potable Water	0.5128	0.4012	-21.8%	1.8712	1.3841	-26.0%
Fertilizer	0.0022	0.0027	+22.7%	0.008	0.0098	+22.5%
O_2	0.1074	0.1285	+19.6%	0.3798	0.4723	+24.4%
Water Vapor	0.5052	0.3982	-21.2%	1.8421	1.3741	-25.4%
Biomass	0.1111	0.1304	+17.4%	0.3896	0.4709	+20.9%

Habitat CO_2 concentration, illustrated in Figure 3, fluctuated between the minimum and maximum target values based on the combined life cycle effects of the plants. Early in the simulation when biomass accumulation is low (before hour 800), the CO_2 produced by humans is being removed, and concentration remains at the top of the target range. When the first crop of plants reaches the point of maximum biomass accumulation (~hour 1000), concentration falls to the bottom of the target range and supplemental CO_2 is added. As the first crop matures, the concentration fluctuates near the bottom of the target range; as the simulation continues and plant life cycles become staggered, the fluctuations become smaller, and the target concentration is mostly maintained.

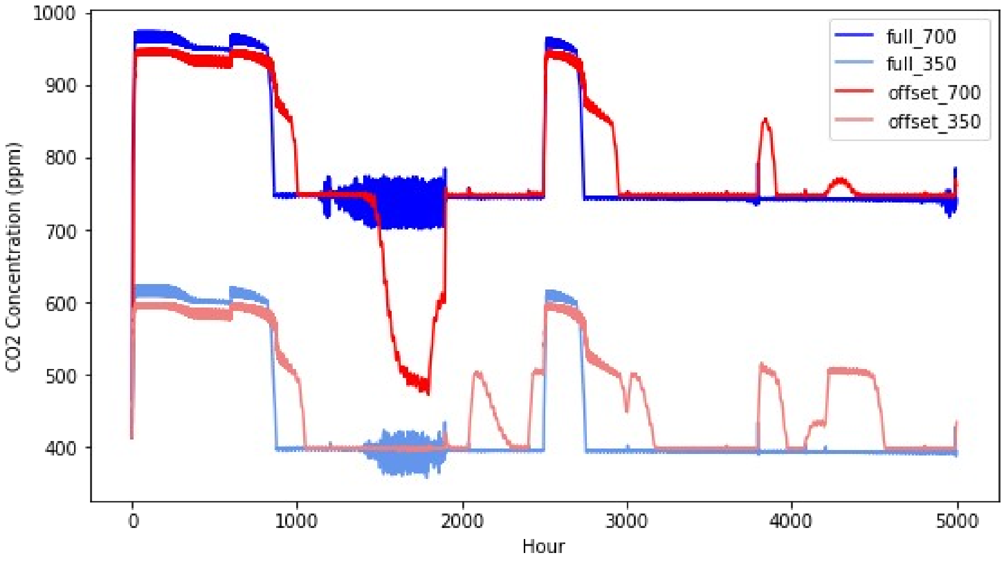

Figure 3. Habitat CO_2 Concentration.

Two differences between the ‘full’ and ‘offset’ scenarios are notable: First, when the initial crop reaches maturity, the CO_2 makeup capacity in the offset scenario is insufficient to maintain the target concentration; however, later on when life cycles are staggered, the combined effect is smaller, and the target concentration can be maintained. Secondly, after ~2800 hours, the ‘offset’ scenario experiences more fluctuation than the ‘full’ scenario. Further experimentation suggests that these fluctuations can be reduced by increasing the greenhouse size, effectively creating a larger buffer.

Two components of the mechanical ECLSS system were affected by eCO_2: the Dehumidifier and the CO_2 Removal SAWD, which remove water vapor and CO_2 respectively from the atmosphere. Electricity used for dehumidification decreased by 12.0% in ‘offset’ and 21.1% in ‘full’, while electricity used for CO_2 reduction decreased by 8.9% in ‘offset’ but increased by 31% in ‘full’. This unexpected increase in electricity used for CO_2 reduction is related to the extra work of maintaining the target CO_2 concentration when currency exchanges are irregular. Considering only the second half of the simulation (after hour 2,500), electricity used for CO_2 reduction decreased by 19.5% in ‘offset’ and increased by just 11.9% in ‘full’. Electricity use for the second half of the simulation for all scenarios is shown in Figure 4.

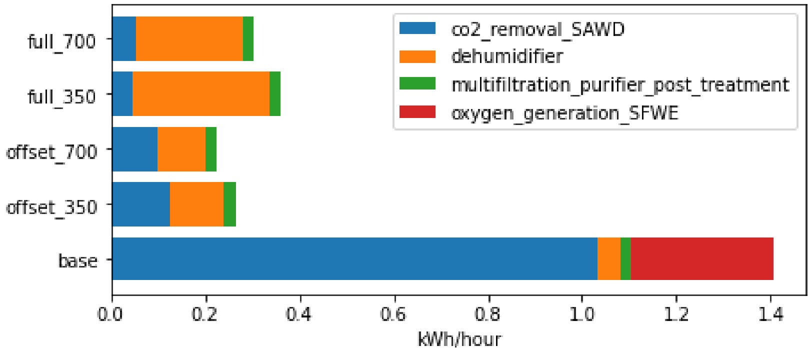

Figure 4. Average Hourly Electricity Use. Selected ECLSS components, after hour 2,500.

VII. Discussion

A. Maximizing the Efficiency of BLSS

Our results suggest that the benefits of plant response to eCO_2 are constrained by the ability to maintain the target CO_2 concentration in the atmosphere, and the benefits of decreased load on mechanical ECLSS are constrained by how efficiently individual components respond to variation in instantaneous plant resource consumption. Efficiency can therefore be improved by reducing the plant resource variation and increasing the sensitivity of mechanical ECLSS components to current conditions.

From a habitat-design perspective, efficiency may be increased by:

- Separating growing areas with independent lighting systems (and a shared atmosphere), which operate on opposing daylight cycles
- Sowing plants in cohorts to maintain an even ‘age’ distribution
- Increasing the size of the shared atmosphere to create a larger buffer
- Employing ECLSS components that can either adjust their rate or switch on-and-off with minimal effect on efficiency
- Algorithmically forecasting the behavior of the BLSS and using this to further increase the efficiency of the mechanical ECLSS components.

B. Secondary Effects

While plants are useful in offsetting human CO_2 production, a garden sized to offset human food consumption (our ‘full’ scenario) produces excess O_2 and requires supplemental CO_2; under eCO_2, these effects are exaggerated. In the ‘full’ scenario, CO_2 demand increased under eCO_2 by .1104 kg/hr, while edible food production increased by just .0306 kg/hr. While this is fine for a habitat on Mars where CO_2 is abundant, for orbital habitats resupplied from Earth, the cost of supplemental CO_2 would outweigh the benefits of increased food production. The excess O_2 builds up in the atmosphere and must be either removed mechanically, using more electricity, or some of the atmosphere must be vented. If the atmosphere has been pressurized with nitrogen, this would require either a resupply from earth or extracting nitrogen from the Martian atmosphere, requiring yet more electricity.

C. Future Work

More accurate results could be obtained through improved modeling techniques, such as:

- Staggering plant growth on a daily and/or lifetime basis
- Conducting simulations at a smaller time step, e.g., 10-minute or 1-minute, instead of 1-hour.
- Using a more sophisticated rate-finding algorithm for mechanical ECLSS components.

The effects of eCO_2 considered here are limited to 700 ppm, as the majority of published research is limited to this level. There is some evidence however (from personal correspondence) that elevating to 1000 or 1500 ppm provides further benefit to C3 crops. Future studies could survey the literature on these higher levels, as well as its affects on human health, and consider scenarios with higher concentrations.

VIII. Conclusion

The plant growth model of SIMOC was expanded to include plant response to atmospheric CO_2 concentration. Simulations were conducted at standard (350 ppm) and elevated (700 ppm) CO_2, and the model performed as expected: CO_2 consumption and biomass production increased, and water consumption and transpiration decreased. We found that the benefits of operating at eCO_2 are limited by the responsiveness and efficiency of the mechanical ECLSS system in maintaining the target CO_2 concentration, and the efficiency could be improved by staggering the plant lifecycles so as to minimize daily and lifetime fluctuation in BLSS capacity.

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